

Dirac right-handed sneutrino dark matter and its signature in the gamma-ray lines

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Abstract

We show that a Dirac right-handed scalar neutrino can be dark matter (DM) as a weakly interacting massive particle in the neutrinophilic Higgs model. When the additional Higgs fields couple only to the leptonic sector through neutrino Yukawa couplings, the right number of relic density of dark matter can be obtained from thermal freeze-out of the dark matter annihilation into charged leptons and neutrinos. At present epoch, this tree-level annihilation into fermions is suppressed by the velocity of dark matter, and the one-loop annihilation cross section into $\gamma\gamma$ can be dominant because relevant coupling constants are different. Hence, the recently observed (tentative) gamma-ray line signal in the Fermi-Fermi-Large Area Telescope can be naturally explained by the annihilation of right-handed sneutrino dark matter.

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I. INTRODUCTION

Various cosmological and astrophysical observations show convincing evidence of non-baryonic dark matter (DM). However, the identity of the dark matter still remains one of the most significant unanswered questions in particle physics and astronomy. One of the most promising and natural candidates may be the weakly interacting massive particles (WIMPs) in the physics beyond the standard model [1].

Much effort has been made in experiments for the direct and indirect detection of WIMP. The strategy for the direct detection of dark matter is to look for the recoil energy from scattering off with nuclei by WIMPs, while that of indirect detection is to find an excess over the astrophysical background of cosmic rays due to additional products by dark matter annihilation or decay. Those annihilation products include neutrinos, positrons, antiprotons, gamma rays and so on.

In general, the gamma-ray flux from dark matter annihilation or decay consists of two components: the continuous spectrum and line spectrum. A gamma-ray line is a clear signature of the WIMP annihilation and has been regarded as a “smoking gun” for the WIMP dark matter because there is no known astrophysical source that can emit such a line gamma ray. However, a tentative indication of gamma-ray line using Fermi-LAT data was reported recently in [2, 3]. It can be associated with dark matter annihilation [2–6] or due to hard photons in the Fermi bubbles regions [7, 8]: however, Ref. [9] confirms the existence of spectral feature and finds no correlation with Fermi bubbles.

In general, the WIMP annihilation cross section into gamma-ray line is small. Since a dark matter candidate by definition does not couple to a photon directly, those annihilation modes are induced by loop processes, and hence, suppressed compared to that of tree level. There are a few nonsupersymmetric models which produce gamma-ray line, e.g., the singlet scalar DM [10], the loop induced neutrino mass model [11], and the inert Higgs doublet model [12]. However, it is not easy to produce in the supersymmetric models. In fact, the expected gamma-ray line flux, in particular $\gamma\gamma$, induced by the annihilation of neutralino in the minimal supersymmetric standard model (MSSM) is much suppressed [13]. Another candidate of WIMP dark matter in the supersymmetric models can be sneutrino: mixed [14] or right-handed sneutrino [15–17]. However, in those models the relevant couplings of sneutrinos are connected to the neutral Higgs bosons or Z' boson, and therefore it is not easy to

produce a large line gamma-ray flux from their annihilation processes.¹

In this paper, we show that a Dirac right-handed sneutrino as WIMP dark matter could produce gamma-ray line flux which is significantly larger than in other supersymmetric models. Right-handed Dirac sneutrino dark matter has been proposed to explain dark matter in the MSSM by introducing right-handed neutrino superfields [19] and in a further extended model [20], but those are not thermal freeze out relics. The essential ingredient for our Dirac sneutrino to be a WIMP is the extended Higgs sector including a neutrinophilic Higgs field, which is a Higgs field interacting with other matters only through neutrino Yukawa couplings [21–24]. The neutrinophilic Higgs model is based on the concept that the smallness of neutrino mass might not come from a small Yukawa coupling but a small vacuum expectation value (VEV) of the neutrinophilic Higgs field H_ν . Recently, various aspects of neutrinophilic Higgs models have been studied [25–32]. The consequence of the neutrinophilic Higgs model is that neutrino Yukawa couplings are not necessarily small because the smallness of neutrino masses is explained by the small H_ν VEV. Actually, neutrino Yukawa couplings can be as large as of the order of unity. Hence we will show that by using this advantage, right-handed Dirac sneutrino can have a large enough annihilation cross section to be WIMP, as well as to produce an observable line gamma-ray flux.

The paper is organized as follows. In Sec. II, we briefly describe a supersymmetric neutrinophilic Higgs model where the VEV of H_ν is small and neutrino Yukawa coupling can be large. In Sec. III, we examine the Dirac right-handed sneutrino dark matter candidate by estimating its thermal relic density and show how large monochromatic gamma-ray line signal can be produced. We then summarize our results in Sec. IV.

II. MODEL

The supersymmetric neutrinophilic Higgs model has a pair of neutrinophilic Higgs doublets H_ν and $H_{\nu'}$ in addition to up- and down-type two Higgs doublets H_u and H_d in the MSSM [29]. A discrete Z_2 parity is also introduced to discriminate $H_u(H_d)$ from $H_\nu(H_{\nu'})$, and the corresponding charges are assigned in Table I. Under this discrete symmetry, the

¹ For the continuous spectrum, a possible significant Breit-Wigner enhancement in s-channel processes has been pointed out [18].

Fields	Z_2 parity	Lepton number
MSSM Higgs doublets, H_u, H_d	+	0
New Higgs doublets, $H_\nu, H_{\nu'}$	−	0
Right-handed neutrinos, N	−	1

TABLE I: The assignment of Z_2 parity and lepton number.

superpotential is given by

$$\begin{aligned}
W = & y_u Q \cdot H_u U_R + y_d Q \cdot H_d D_R + y_l L \cdot H_d E_R + y_\nu L \cdot H_\nu N \\
& + \mu H_u \cdot H_d + \mu' H_\nu \cdot H_{\nu'} + \rho H_u \cdot H_{\nu'} + \rho' H_\nu \cdot H_d,
\end{aligned} \tag{1}$$

where we omit generation indexes and dot represents $SU(2)$ antisymmetric product. The Z_2 parity plays a crucial role of suppressing tree-level flavor changing neutral currents (FCNCs) and is assumed to be softly broken by tiny parameters of ρ and $\rho' (\ll \mu, \mu')$.

The scalar potential relevant for Higgs fields and sneutrinos is given by the supersymmetry (SUSY) potential and SUSY breaking terms,

$$V = V_{\text{SUSY}} + V_{\text{soft}}, \tag{2}$$

with

$$\begin{aligned}
V_{\text{SUSY}} = & |y_l H_d \tilde{E}_R + y_\nu H_\nu \tilde{N}|^2 + |y_\nu \tilde{L} \tilde{N} - \mu' H_{\nu'} + \rho' H_d|^2 + |y_\nu \tilde{L} \cdot H_\nu|^2 + |y_l \tilde{L} \cdot H_d|^2 \\
& + |\mu H_d + \rho H_{\nu'}|^2 + |y_l \tilde{L} \tilde{E}_R + \mu H_u + \rho' H_\nu|^2 + |\mu' H_\nu + \rho H_u|^2 + \text{D-terms},
\end{aligned} \tag{3}$$

and

$$\begin{aligned}
V_{\text{soft}} = & m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_{H_\nu}^2 |H_\nu|^2 + m_{H_{\nu'}}^2 |H_{\nu'}|^2 + m_{\tilde{L}}^2 |\tilde{L}|^2 + m_{\tilde{N}}^2 |\tilde{N}|^2 \\
& + (y_l A_l \tilde{L} \cdot H_d \tilde{E}_R + y_\nu A_\nu \tilde{L} \cdot H_\nu \tilde{N} \\
& + B\mu H_u \cdot H_d + B'\mu' H_\nu \cdot H_{\nu'} + B_\rho \rho H_u \cdot H_{\nu'} + B_{\rho'} \rho' H_\nu \cdot H_d + h.c.).
\end{aligned} \tag{4}$$

The Higgs dependent part of the scalar potential is expressed as

$$\begin{aligned}
V = & |-\mu' H_{\nu'} + \rho' H_d|^2 + |\mu H_d + \rho H_{\nu'}|^2 + |\mu H_u + \rho' H_\nu|^2 + |\mu' H_\nu + \rho H_u|^2 + \text{D-terms} \\
& + m_{H_u}^2 |H_u|^2 + m_{H_d}^2 |H_d|^2 + m_{H_\nu}^2 |H_\nu|^2 + m_{H_{\nu'}}^2 |H_{\nu'}|^2 \\
& + (B\mu H_u \cdot H_d + B'\mu' H_\nu \cdot H_{\nu'} + B_\rho \rho H_u \cdot H_{\nu'} + B_{\rho'} \rho' H_\nu \cdot H_d + h.c.).
\end{aligned} \tag{5}$$

The tiny soft Z_2 -breaking parameters ρ, ρ' generate a large hierarchy of $v_{u,d}(\equiv \langle H_{u,d} \rangle) \gg v_{\nu,\nu'}(\equiv \langle H_{\nu,\nu'} \rangle)$, which are given by the stationary conditions

$$\begin{pmatrix} m_{H_\nu}^2 + \mu'^2 + \frac{m_Z^2 \tan^2 \beta - 1}{2 \tan^2 \beta + 1} & -B_{\mu'} \mu' \\ -B_{\mu'} \mu' & m_{H_{\nu'}}^2 + \mu'^2 - \frac{m_Z^2 \tan^2 \beta - 1}{2 \tan^2 \beta + 1} \end{pmatrix} \begin{pmatrix} v_\nu \\ v_{\nu'} \end{pmatrix} \simeq \begin{pmatrix} -(\mu' \rho + \mu \rho') & B_{\rho'} \rho' \\ B_\rho \rho & -(\mu \rho + \mu' \rho') \end{pmatrix} \begin{pmatrix} v_u \\ v_d \end{pmatrix}. \quad (6)$$

Namely, we obtain

$$v_\nu = \mathcal{O}\left(\frac{\rho}{\mu'}\right) v. \quad (7)$$

The hierarchy of $\rho/\mu' \ll 1$ leads to a small v_ν and the smallness of ρ compared to μ' is explained naturally in 't Hooft's sense because ρ is a soft breaking parameter of the Z_2 parity. It is easy to see that neutrino Yukawa couplings y_ν can be large for small v_ν using the relation of the Dirac neutrino mass $m_\nu = y_\nu v_\nu$. For $v_\nu \sim 0.1$ eV, it gives $y_\nu \sim 1$.

At the vacuum of $v_{\nu,\nu'} \ll v_{u,d}$ that we are interested in, physical Higgs bosons originated from $H_{u,d}$ are almost decoupled from those from $H_{\nu,\nu'}$, except a tiny mixing of the order of $\mathcal{O}(\rho/M_{\text{SUSY}}, \rho'/M_{\text{SUSY}})$ where $M_{\text{SUSY}} (\sim 1 \text{ TeV})$ denotes the scale of soft SUSY breaking parameters. The former $H_{u,d}$ doublets almost constitute Higgs bosons in the MSSM - two CP-even Higgs bosons h and H , one CP-odd Higgs boson A , and a charged Higgs boson H^\pm - while the latter, $H_{\nu,\nu'}$, constitutes two CP-even Higgs bosons $H_{2,3}$, two CP-odd bosons $A_{2,3}$, and two charged Higgs bosons $H_{2,3}^\pm$.

The scalar potential including sneutrinos is given by

$$\begin{aligned} V = & |y_\nu H_\nu \tilde{N}|^2 + |y_\nu \tilde{L} \tilde{N} - \mu' H_{\nu'} + \rho' H_d|^2 + |y_\nu \tilde{L} \cdot H_\nu|^2 + |y_l \tilde{L} \cdot H_d|^2 \\ & + m_L^2 |\tilde{L}|^2 + m_{\tilde{N}}^2 |\tilde{N}|^2 + (y_l A_l \tilde{L} \cdot H_d \tilde{E}_R + y_\nu A_\nu \tilde{L} \cdot H_\nu \tilde{N} + h.c.) + \text{D - terms}. \end{aligned} \quad (8)$$

The mixing between LH and RH sneutrino is roughly estimated as

$$\sin \theta_{\tilde{\nu}} = \mathcal{O}\left(\frac{m_\nu}{M_{\text{SUSY}}}\right). \quad (9)$$

We find that the RH sneutrino \tilde{N} , which is a dark matter candidate in our model, has suppressed interactions to the SM-like Higgs boson or Z boson since they are proportional to the mixing of LH and RH neutrinos, $\sin \theta_{\tilde{\nu}}$ in Eq. (9).

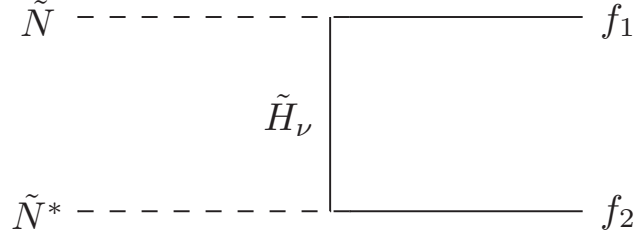


FIG. 1: Tree-level diagram for the annihilation of right-handed sneutrinos.

III. RIGHT-HANDED SCALAR NEUTRINO AS DARK MATTER

In this section we will investigate the thermal relic abundance of the right-handed sneutrino dark matter \tilde{N} and its indirect signature in the gamma-ray observation.

A. Thermal relic density of dark matter : Tree-level annihilation of \tilde{N}

Since the dark matter particle \tilde{N} can have large Yukawa couplings given by $y_\nu \sim \mathcal{O}(1)$, the DMs can be in the thermal equilibrium in the early Universe through these large Yukawa interactions. Here, we consider the case that the mass eigenstates H_2 and H_3 originated mostly from H_ν and $H_{\nu'}$ are much heavier than $M_{\tilde{N}}$ then the electroweak precision measurement constraints are easily satisfied and the annihilation into H_ν and $H_{\nu'}$ is kinematically forbidden. In this case, the dominant annihilation mode of \tilde{N} in the early Universe is the annihilation into a lepton pair $\tilde{N}\tilde{N}^* \rightarrow \bar{f}_1 f_2$ mediated by the heavy H_ν -like Higgsinos as described in Fig. 1. The final states f_1 and f_2 are charged leptons for the t -channel \tilde{H}_ν -like charged Higgsino (\tilde{H}_ν^\pm) exchange, while those are neutrinos for the t -channel \tilde{H}_ν -like neutral Higgsino (\tilde{H}_ν^0) exchange.

The thermal averaged annihilation cross section for this mode in the early Universe is expressed in partial wave expansion method as [33]

$$\langle \sigma v \rangle = \sum_f \left(\frac{y_\nu^4}{16\pi} \frac{m_f^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} + \frac{y_\nu^4}{8\pi} \frac{M_{\tilde{N}}^2}{(M_{\tilde{N}}^2 + M_{\tilde{H}_\nu}^2)^2} \frac{T}{M_{\tilde{N}}} + \dots \right), \quad (10)$$

where we used $\langle v_{\text{rel}}^2 \rangle = 6T/M_{DM}$ with v_{rel} being the relative velocity of annihilating dark matter particles, and m_f is the mass of the fermion f and $M_{\tilde{H}_\nu} \simeq \mu'$ denotes the mass of \tilde{H}_ν -like Higgsino. For simplicity we have assumed that Yukawa couplings are universal for each flavor.

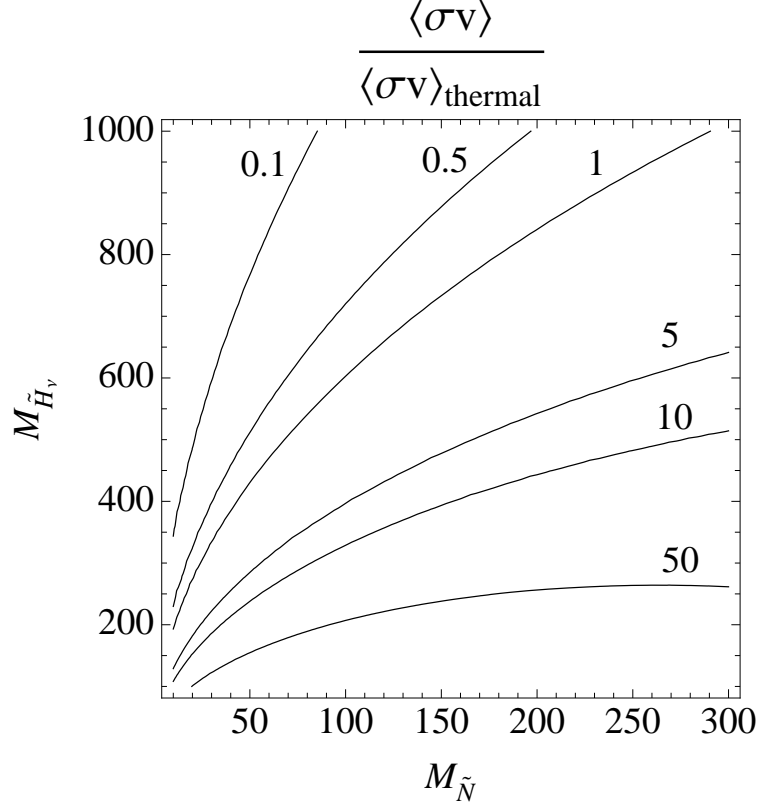


FIG. 2: The thermal averaged annihilation cross section of \tilde{N} at freeze-out temperature normalized by that required for the right relic density of WIMP. Here we used $T/M_{\tilde{N}} = 1/20$ and $y_\nu = 1$.

Since the s -wave contribution of the first term in the right-hand side is helicity suppressed, the p -wave annihilation cross section of the second term is relevant for the dark matter relic density at freeze-out epoch, $T_f \sim M_{\tilde{N}}/20$. The right relic density of WIMP can be obtained for the thermal averaged annihilation cross section:

$$\langle \sigma v \rangle_{\text{thermal}} \simeq 3 \times 10^{-26} \text{ cm}^3 \text{ s}^{-1} = 2.57 \times 10^{-9} \text{ GeV}^{-2}. \quad (11)$$

Comparing Eqs. (10) and (11), we find $y_\nu = \mathcal{O}(1)$ as

$$y_\nu^4 \simeq 1.09 \left(\frac{130 \text{ GeV}}{M_{\tilde{N}}} \right)^2 \left(\frac{M_{\tilde{H}_\nu}}{700 \text{ GeV}} \right)^4 \left(\frac{\langle \sigma v \rangle_{\text{thermal}}}{2.57 \times 10^{-9} \text{ GeV}^{-2}} \right) \left(\frac{1/20}{T_f/M_{\tilde{N}}} \right), \quad (12)$$

where T_f is the DM freeze-out temperature, which is usually $T_f \simeq M_{DM}/20$, and we accounted for the number of modes of the final states $\sum_f = 2 \times 3^2 = 18$. In Fig. 2 we show the contour plot of the annihilation cross section in the plane of $M_{\tilde{N}}$ and $M_{\tilde{H}_\nu}$ for $y_\nu = 1$.

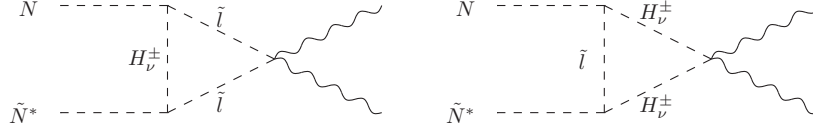


FIG. 3: Triangle loop diagrams for the annihilation of right-handed sneutrinos.

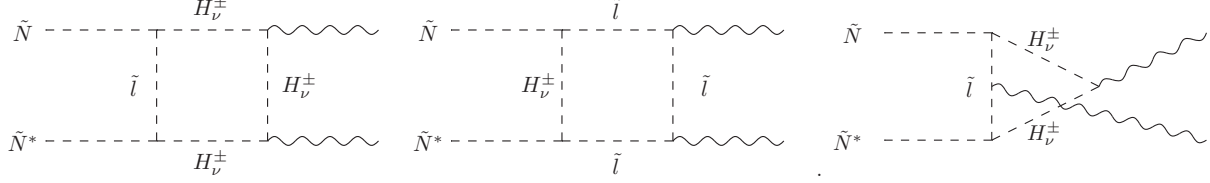


FIG. 4: Box loop diagrams for the annihilation of right-handed sneutrinos.

B. Monochromatic gamma-ray lines from right-handed sneutrino annihilation

Since we are considering the massive dark matter, which is nonrelativistic at present, the tree-level p-wave contribution to the annihilation of DM in Eq. (10) is also suppressed. Therefore, in this model, the dominant contribution to the annihilation of DM in the galaxy at present universe comes from the loop diagrams.

The emission of a vector boson through the virtual internal bremsstrahlung can enhance the s -wave contribution in particular when the mass splitting between dark matter and the t -channel mediator, H_ν in our case, is small. However since we are considering heavy Higgs, $M_{H_\nu} \gg M_{\tilde{N}}$, the bremsstrahlung is suppressed. Therefore we do not expect the line spectrum of gamma ray from internal bremsstrahlung, which is different from that in [2].

The charged components of the H_ν scalar doublet and charged scalar fermions make the triangle or box loop-diagram shown in Figs. 3 and 4, and the two photons can be emitted from the internal charged particles. In this case, the photons have line spectrum with energy

$$E_{2\gamma} = M_{\tilde{N}}. \quad (13)$$

In the triangle diagrams, H_ν and \tilde{l} are in the loop and the charged lepton or charged Higgs have a quartic coupling with photons. In this analysis we neglect those fermion loop processes because the triangle diagrams with fermions are helicity suppressed and its leading terms are dimension-six operators. For the box diagrams, the charged Higgs H_ν^\pm and charged sleptons

in the loop emit two photons. Thus the amplitude is the sum of all the contributions

$$\mathcal{M}_{2\gamma} = \mathcal{M}_{2\gamma}^{\text{Tringle}} + \mathcal{M}_{2\gamma}^{\text{Box}}. \quad (14)$$

Since DM is nonrelativistic we can ignore the momentum of DM. Assuming $M_{H_\nu}, M_{\tilde{l}} \gg M_{\tilde{N}}$, we obtain the annihilation cross section to two photons via one loop as

$$\langle\sigma v\rangle_{2\gamma} = \frac{|M|_{2\gamma}^2}{32\pi M_{\tilde{N}}^2} \simeq \frac{\alpha_{\text{em}}^2 y_\nu^4 (A_\nu^2 + \mu'^2)^2}{8\pi^3} \frac{4}{M_{\tilde{l}}^4 M_{\tilde{N}}^2}. \quad (15)$$

in the limit of $M_{H_\nu} = M_{H'_\nu} = M_{\tilde{l}}$ for simplicity.

The gamma-ray line spectrum can also be produced from the dark matters annihilation into $Z\gamma$ through box one-loop. The energy of the photons produced in this process is

$$E_{1\gamma} \simeq M_{\tilde{N}} \left(1 - \frac{M_Z^2}{4M_{\tilde{N}}^2} \right). \quad (16)$$

The annihilation cross section is approximately given by

$$\langle\sigma v\rangle_{1\gamma} \simeq \frac{\alpha_{\text{em}}^2}{8\pi^3 \cos^2 \theta_w} \frac{y_\nu^4 (A_\nu^2 + \mu'^2)^2}{M_{\tilde{l}}^4} \frac{4}{M_{\tilde{N}}^2} \left(1 - \frac{M_Z^2}{4M_{\tilde{N}}^2} \right), \quad (17)$$

where θ_w is Weinberg mixing angle and we used $M_{H_\nu} = M_{H'_\nu} = M_{\tilde{l}}$.

Recently a tentative indication of gamma-ray line using Fermi-LAT data was reported in [2, 3]. When it is interpreted in terms of dark matter particles annihilating into a photon pair, the observation implies a dark matter mass of [3]

$$m_\chi = 129.8 \pm 2.4_{-13}^{+7} \text{ GeV}, \quad (18)$$

and a partial annihilation cross section of

$$\langle\sigma v\rangle_{\chi\chi \rightarrow \gamma\gamma} = (1.27 \pm 0.32_{-0.28}^{+0.18}) \times 10^{-27} \text{ cm}^3 \text{ s}^{-1}, \quad (19)$$

when using the Einasto dark matter profile.

The right-handed scalar neutrino dark matter in this model can explain this observation perfectly with mass $M_{\tilde{N}} = 130 \text{ GeV}$. The gamma-ray line signal in the Fermi-LAT can be explained when

$$\langle\sigma v\rangle_{(\tilde{N}\tilde{N}^* \rightarrow \gamma\gamma)} = \langle\sigma v\rangle_{(\chi\chi \rightarrow \gamma\gamma)}^{\text{Fermi-LAT}}. \quad (20)$$

This corresponds to the coupling

$$y_\nu^4(A_\nu^2 + \mu'^2)^2 \simeq 1.8 M_{\tilde{l}}^4, \quad (21)$$

where we used $M_{\tilde{N}} = 130 \text{ GeV}$ and $\alpha_{em} = 1/127$. For this mass of DM, we have another gamma-ray line at $E_\gamma = 114 \text{ GeV}$ but the flux is reduced by half that of two gamma line at 130 GeV .

C. Another constraint

Here we note the constraint from direct dark matter searches. The relevant processes for sneutrino DM direct searches are Z boson and Higgs boson exchange. As we note in Eq. (9), due to extremely small left-right mixing of sneutrinos, the couplings are considerably suppressed by $\mathcal{O}((m_\nu/M_{\text{SUSY}})^2)$. However, there is an additional Z boson exchange process induced at one loop by the left-handed (LH) sneutrino and neutrinophilic Higgs (H_ν or $H_{\nu'}$) or those corresponding to $SU(2)$ doublet charged particles. In fact, the effective coupling between right-handed sneutrino \tilde{N} and a quark through the Z boson induced by the LH sneutrino and H_ν -like Higgs boson loop is

$$\mathcal{L}_{\text{int}} = \left(\frac{y A_\nu}{4\pi} \right)^2 \frac{1}{12M^2} \left(\frac{-g_2}{2 \cos \theta_W} \right) \frac{g_2(T - Q \sin^2 \theta_W)}{M_Z^2 \cos \theta_W} 2p_\mu \tilde{N} \tilde{N}^* \bar{q} \gamma^\mu q, \quad (22)$$

where p is the four momentum of \tilde{N} in the nonrelativistic limit, M_Z is the Z boson mass, g_2 is the $SU(2)_L$ gauge coupling, θ_W is the Weinberg angle, and M is the mass of the LH sneutrino and H_ν -like Higgs boson. For the TeV scale mass of those particles inside loops, we find the cross section with a nucleon as

$$\sigma^{\text{SI}} \simeq 10^{-9} \text{ pb}. \quad (23)$$

Hence, in fact, it will be possible to explore this model by direct dark matter search experiments in the near future.

IV. CONCLUSION

We have shown that a Dirac right-handed sneutrino with neutrinophilic Higgs doublet fields is a weakly interacting massive particle and a viable dark matter candidate. This

is because neutrino Yukawa couplings can be as large as of the order of unity in models with neutrinophilic Higgs where the smallness of neutrino masses is explained by the small H_ν VEV. The promising signature of this sneutrino comes from the indirect detection of dark matter, especially gamma-ray lines. One-loop annihilation cross section into $\gamma\gamma$ can be larger than the cross section of the helicity suppressed tree-level annihilation into fermions. Hence we can expect a large gamma-ray line signal, and for instance, signals which might have been observed in the Fermi-LAT can be explained by its annihilation.

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